4th INTERNATIONAL CONFERENCE ON NDT
Hellenic Society for NDT
11-14 October 2007, Chania, Crete-Greece

Quality assessment of a laser cut based on captured acoustic emission signals

Janez GRUM, Tomaž KEK

University of Ljubljana, Faculty of Mechanical Engineering,
Aškerčeva 6, 1000 Ljubljana, Slovenia,
E-mails: janez.grum@fs.uni-lj.si, tomaz.kek@fs.uni-lj.si,

Abstract
The paper presents results of an analysis of acoustic emission (AE) measurement in laser cutting of a DC04 steel plate. Laser cutting was evaluated on the basis of monitoring the acoustic emission in the course of cutting and of an analysis of events occurring in the material after the completion of laser cutting. It was found that the cutting oxygen flow was the primary source of AE in laser cutting. The incidence of the supersonic gas flow in the cutting front is reflected at an acoustic sensor in the form of continuous AE signals. The AE measured immediately after laser cutting is a result of various events in the heat-affected zone surrounding the laser cut and of the dross formed at the lower edge of the cut. It was proved that laser-cutting conditions set exerted a significant influence on the amplitude value and signal intensity of AE during and after cutting. It was confirmed separately that there is also a relation between a measured AE signal and dross formation at the lower edge of the cut..

Keywords: Acoustic emission, continuous emission, burst emission, PZT sensor, laser cutting, dross.

1 Introduction

In laser processing an interaction between a laser beam and a shielding or cutting gas with a workpiece material shows in various physical and chemical phenomena at the zone of interaction. In the presence of a reactive gas a high power-density laser beam will provide rapid heating, melting and even evaporation of the material. This will be accompanied by propagation of electromagnetic waves and acoustic emission from the interaction point, which can be captured at various locations. Electromagnetic waves and acoustic emission provide ample information on the process suitable for the assessment of laser-processing quality.
Acoustic emission occurring during laser cutting provides signal variations characteristic of physical phenomena in the cutting front. Thermal expansion and shrinkage of the material will cause varying of the stress condition next to the cutting front. Solidification of the molten material with martensitic phase transformation contributes to the occurrence of acoustic emission after laser-beam passage [1]. The acoustic emission also indicates changes in internal stresses in the material during the cooling process and eventually shows the magnitude of residual stresses. Material evaporation in the cutting zone and the plasma formed produce AE, which can be measured in the surrounding gas and the workpiece material [2]. The acoustic emission indicates very dynamic phenomena in the cutting front, which are related to the melt expulsion from the cutting front during the cutting process. The influence of the shielding or cutting gas at the interaction zone is strong as well, which can be efficiently monitored by capturing AE signals [3].
Several studies of the laser cutting process and analyses of acoustic emission measured with microphones close to the cutting front were made [4, 5]. A basic hypothesis is that acoustic emission is due to resonance occurring when the gas flow hits the cutting front. It turned out that the resonance frequency of the acoustic emission measured was important because it permitted the assessment of cut geometry and quality. Unfortunately, data on analyses of acoustic emission captured with contact PZT sensors, which would permit a description of the phenomena in a material in laser cutting, are scarce. In the present paper the acoustic emission captured with a PZT sensor, which permits a prediction of various phenomena in the material during and after laser cutting, will be treated. Monitoring of acoustic emission thus gives an insight into the state of a working process and permits carrying out of control actions in order to accomplish a quality laser cutting process.

2 Eksperimental procedure

Plate cutting was performed with an industrial CO_2 laser processing system Spectra Physics 820, which has a maximum output power of 1500 W and a Gaussian power distribution (TEM_{00}). The laser head chosen had a focusing distance of 127 mm and an output diameter of a conical nozzle of 2,2 mm. In cutting, oxygen with an overpressure of 0,2 MPa was used as a cutting gas. During cutting the focus of the convergence lens was positioned 0,5 mm below the surface of the plate with thickness δ = 1,5 mm. Laser cutting was carried out at a plate of common structural steel designated DC04 in accordance with EN 10027-1. The steel chosen is used in automotive industry to produce body parts. During the process the plate was positioned on a workbench on a soft rubber support to prevent noise during the laser cutting process. 0,5 m long parallel cuts with spans of 2 cm were made at the plate under different cutting conditions. The cutting process is shown in Figure 1. The cutting conditions chosen, including the energy input per unit of cut length E_d, are given in Table 1.

A measurement device for measuring acoustic emission AMSY4 produced by Vallen Systeme GmbH and a contact PZT sensor VS150-M were used to capture acoustic emission. The sensor makes it possible to register ultrasonic waves in a frequency range from 100 to 450 kHz, the strongest response being at 150 kHz. Good acoustic coupling of the sensor with the surface was accomplished with coupling silicon grease.

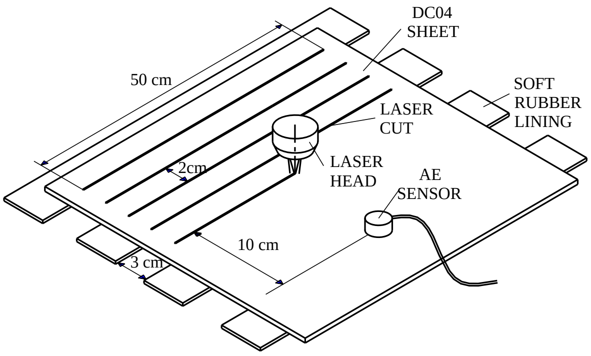


Figure 1: Representation of cutting procedure and position of sensor to capture acoustic emission during and after cutting

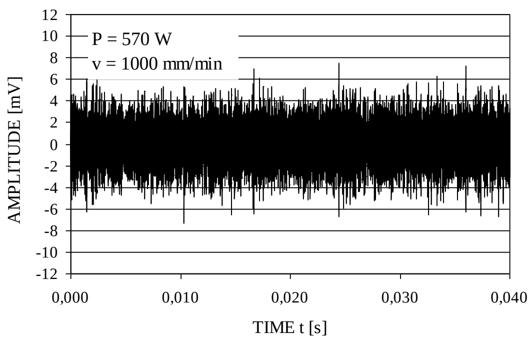
Table 1: Chosen laser-cutting conditions

P [W]	v [mm/min]	E_d [kJ/m]
430	1000	25,8
430	1500	17,2
430	2000	12,9
430	2500	10,3
500	1000	30,0
500	1500	20,0
500	2000	15,0
500	2500	12,0
570	1000	34,2
570	1500	22,8
570	2000	17,1
570	2500	13,7
640	1000	38,4
640	1500	25,6
640	2000	19,2
640	2500	15,4

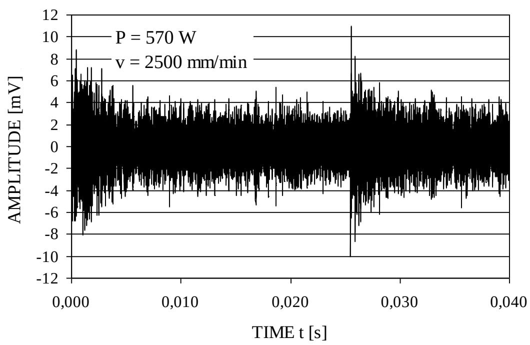
3 Eksperimental results

3.1 Continuous AE signals in laser cutting

A turbulent cutting-gas flow during the cutting process permits capturing of continuous AE signals by PZT sensor. Figure 2 shows two captured voltage signals of acoustic emission in cutting with power P = 570 W and with different speeds v. The different cutting conditions used produced different laser-cut widths, different inclinations of the cutting front, different melt thicknesses and fractions of the material removed from the cutting front [7, 8]. This reflects in the cutting-gas flow, which advances into a laser notch and, consequently, in the acoustic emission measured in the material. A reduction of the energy input at the interaction zone due to an increase in the cutting speed or a reduction of the laser-beam power shows in a reduction of the fraction of oxidized melt, a lower melt temperature and, consequently, in increased melt viscosity. At the lower edge of the laser cut droplets will form. When the force due to the gas pressure in the cutting front does not exceed the force due to surface tension of the melt, solidification of the melt will occur at the lower edge of the laser cut and, consequently, produce a dross. Solidification of the molten material, particularly at the lower edge of the laser cut and cracking of the oxide coating produce AE bursts in a continuous signal. Distinctive AE outbursts increase the amplitude of the continuous AE signal.



a)



b)

Figure 2: Records of continuous AE signals: a) quality cut without any dross and b) poorer cut quality with dross

Research results show that the amplitude of the AE signal is a very suitable parameter to be used in the assessment of laser-cutting quality. In order to assess the measured AE signals, an average of amplitudes m_A of a series of 20 consecutive signals of continuous acoustic emission under the given cutting conditions was used. The signal amplitude is the strongest deviation of a voltage signal from a zero axis in the time of signal duration. An analysis of the laser cutting process showed that continuous signals with a specified time interval of signal duration, i.e. 0,1 s, are suitable for its control. A supposition of an influence of individual factors on the variable analysed was confirmed by a factorial analysis including analysis of variance.

Results of the analysis of variance of the amplitude average of the continuous AE signals m_A are given in Table 2. The experimental procedure was performed with three repetitions with the given combinations of the processing conditions. The influence of the laser-beam power (P) and cutting speed (v) on the signal-amplitude average m_A was analysed. It was found that linear effect of laser-beam power M_L, linear H_L and quadratic H_Q effects of the cutting speed and interactions MH_{LxL} and MH_{KxQ} are significant. The F_0 test statistics representing a ratio of mean squares and which belongs to the Snedecor distribution F is given in Table 2.

Table 2: An expanded analysis of the variance of the amplitude average of continuous AE signals.

Source of variation	Sum of squares SS_i [db^2]	Degrees of freedom ν_i	Mean square MS_i [db^2]	F_0	$F_{0,05,\nu i,32}$
Power	51,76	3	17,253	11,783	2,9
M_L	51,21	1	51,210	34,975	5,54
M_Q	0,43	1	0,434	0,297	5,54
M_K	0,11	1	0,115	0,078	5,54
Cutting sp.	163,13	3	54,377	37,138	2,9
H_L	98,66	1	98,662	67,383	5,54
H_Q	64,42	1	64,422	43,998	5,54
H_K	0,05	1	0,048	0,033	5,54
Interaction	135,45	9	15,050	10,279	2,19
MH_{LxL}	110,77	1	110,765	75,649	5,54
MH_{LxQ}	0,01	1	0,010	0,007	5,54
MH_{LxK}	5,44	1	5,440	3,715	5,54
MH_{QxL}	0,11	1	0,109	0,075	5,54
MH_{QxQ}	3,60	1	3,603	2,461	5,54
MH_{QxK}	2,07	1	2,075	1,417	5,54
MH_{KxL}	3,54	1	3,539	2,417	5,54
MH_{KxQ}	9,90	1	9,898	6,760	5,54
MH_{KxK}	0,01	1	0,009	0,006	5,54
Error	46,85	32	1,464		
Total	397,19	47			

Indices L, Q, K – linear, quadratic and cubic effects of power designated M and of cutting speed designated H, i.e. their interaction MH. A more detailed definition can be found in Ref. [6].

The amplitude of AE signals A_{AE} can be given in the form of voltage [mV] but in the treatment of acoustic emission the signal amplitude is usually given in decibels [db]. The expression to transform a voltage signal into decibels is written:

$$A_{AE} = 20 \log \left(|V(t_m)|/V_r\right) \quad (1),$$

where $V(t_m)$ is the strongest deviation of the measured signal voltage from the zero axis that occurs at the moment t_m, V_r is the reference input voltage of the pre-amplifier (in our case V_r = 0,001 mV).

The AE signals captured in laser cutting served to determine functional dependence between the laser-beam power (P), cutting speed (v), and the amplitude average of AE signals m_A. Because of the same distance among individual levels of quantitative factors, the method of orthogonal polynomials was chosen to determine a polynomial regression model.

The amplitude average of AE signals is described with an approximation polynomial:

$$\begin{aligned} m_A &= 78{,}53 - 0{,}4619P_1(P) + 0{,}6412P_1(v) + 1{,}1585P_2(v) - \\ &0{,}3038P_1(P)P_1(v) - 0{,}2031P_3(P)P_2(v) + 0{,}2740P_2(P)P_2(v) - \\ &0{,}0543P_3(P)P_1(v) - 0{,}0673P_1(P)P_3(v) \end{aligned} \quad (2),$$

where $P_i(P)$ and $P_i(v)$ are the orthogonal polynomials [6] that are specified by the equations:

$$P_1(P) = \frac{(P-535)}{35} \quad (3),$$

$$P_2(P) = \left(\frac{(P-535)}{70}\right)^2 - 1{,}25 \quad (4),$$

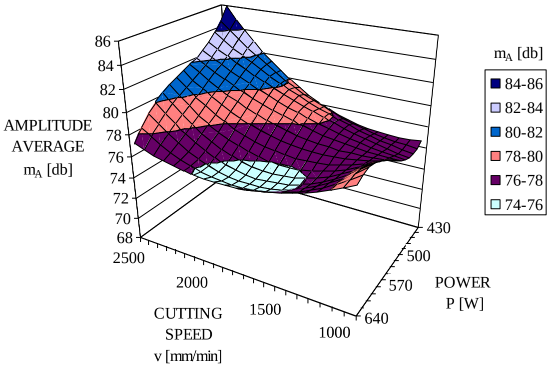
$$P_3(P) = 3{,}\bar{3}\left[\left(\frac{P-535}{70}\right)^3 - \left(\frac{P-535}{70}\right)2{,}05\right] \quad (5),$$

$$P_1(v) = \frac{v-1750}{250} \quad (6),$$

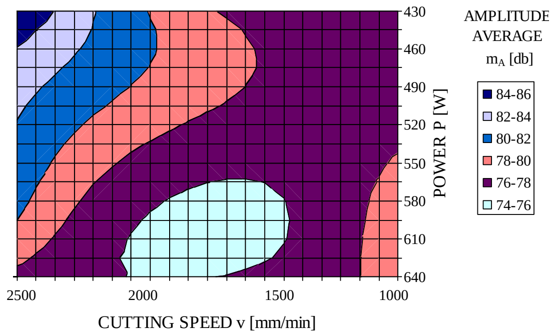
$$P_2(v) = \left(\frac{v-1750}{500}\right)^2 - 1{,}25 \quad (7),$$

$$P_3(v) = 3{,}\bar{3}\left[\left(\frac{v-1750}{500}\right)^3 - \left(\frac{v-1750}{500}\right)2{,}05\right] \quad (8).$$

For the approximation of the response surface, usually significant effects from the analysis of variance are taken into account. These are the most distinctive effects on the signal amplitude average m_A. Taking into account some more insignificant effects in the approximation polynomial, the deviations between the measured and calculated signal amplitude averages will be reduced. In addition to the significant effects mentioned in Equation (2) for the response surface, three more effects, having a slightly lesser influence than the significant level, are taken into account. These effects are: MH_{LxK}, MH_{QxQ} and MH_{KxL}. Figure 3 shows a 3D response surface for a signals amplitude average m_A, established in equation (2). Calculation of the approximation polynomials makes it possible to predict averages m_A within the scope of tested cutting conditions.



(a) 3D response surface



(b) contour plot

Figure 3: 3D and contoured representation of relation between signals amplitude average m_A and laser-cutting conditions

Figure 4 shows a comparison of the values m_A calculated with the approximation polynomial given by equation (2) and cell averages $\overline{m}_{A,ij.}$. $\overline{m}_{A,ij.}$ is a cell average for the amplitude averages of continuous AE signals m_A, which were measured in the repetitions of the experiment under the laser-cutting condition chosen for the plate.

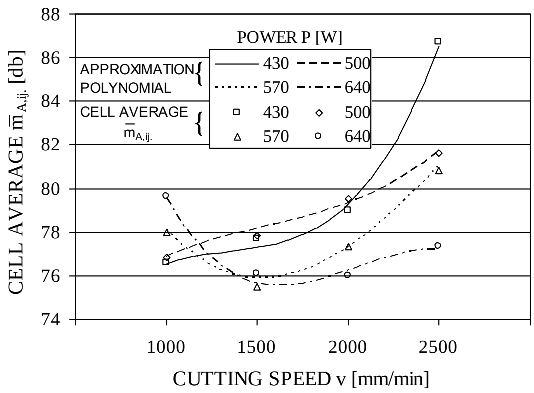


Figure 4: Curves of approximation polynomial (2) and cell averages $\overline{m}_{A,ij.}$

The waveform of the AE signals makes it possible to assess a signal also by means of other parameters such as signal energy, signal duration, signal rise time, decay time, acoustic emission count and others. Signal energy [1] is proportional to signal intensity, which is defined by a signal square integral,

$$I_{AE} = \int_0^{\infty} |V(t)|^2 dt \qquad (9).$$

In view of higher reliability of the assessment of the measured AE signals, the intensity average m_I of a series of 20 consecutive continuous AE signals captured under the given cutting conditions was taken as a basis. A time interval of the continuous signal of 0,1 s was chosen for evaluation. Figure 5 shows changes of the intensity average of AE signals under the given cutting conditions. The response surface is determined with a statistical analysis of the data obtained from AE signals with the method of orthogonal polynomials.

Changing of the intensity average m_I as a function of laser-beam power (P) and cutting speed (v) can be written as an approximation polynomial

$$m_I = 289{,}620 - 10{,}132 P_1(P) + 18{,}003 P_2(P) + 44{,}189 P_2(v) - 12{,}879 P_1(P) P_1(v) + 10{,}012 P_1(P) P_2(v) - 3{,}830 P_1(P) P_3(v) \quad (10).$$

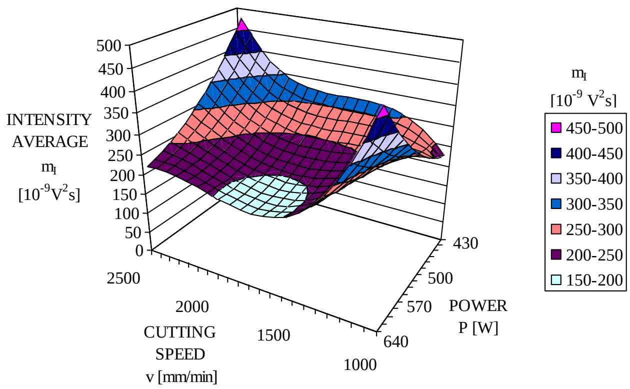


Figure 5: Intensity average m_I of AE signals under given laser-cutting conditions

From a comparison of the response surface for the AE signals amplitude average m_A (Figure 4a) and of the AE signals intensity average m_I (Figure 5), it can be inferred that an increase in AE signal amplitude is followed by an increase in the AE signal intensity. The lowest average m_A may be expected with a cutting condition P = 610 W, v = 1750 mm/min, and the lowest average m_I at a cutting condition P = 625 W, v = 1750 mm/min, which shows a close coincidence of the two chosen characteristics of the captured AE signals at lower values. Figure 6 shows a relation between the amplitude averages $m_{A,ijk}$ and intensity averages $m_{I,ijk}$ of the AE signals. $m_{A,ijk}$ and $m_{I,ijk}$ designate the average values with the i^{th} level of the laser-beam power, the j^{th} level of the cutting speed, the k^{th} measurement repetition with the individual combination of power and cutting speed. The correlation coefficient (r) is defined by the equation

$$r = \frac{Cov(m_A, m_I)}{\sqrt{Var(m_A)\,Var(m_I)}} \qquad (11).$$

An analysis of acoustic emission will confirm that the correlation coefficient between the amplitude averages $m_{A,ijk}$ and intensity averages $m_{I,ijk}$ of the voltage signals of AE captured is good, i.e. r = 0.83. In Figure 6 an ellipse marks the zone of acoustic emission measured, which corresponds to an acceptable quality of laser cutting with an appertaining small dross (O ≤ 2). More on the influence of the laser-cutting conditions on the size of dross and, consequently, on cutting quality is said in chapter 3.3.

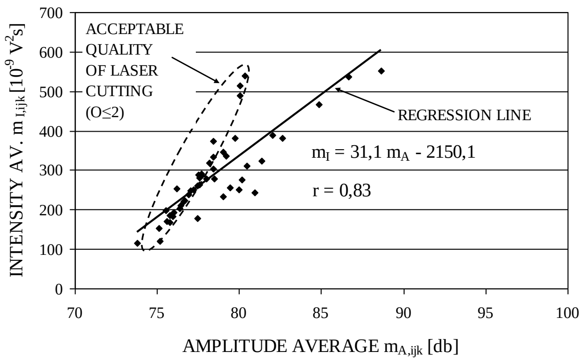


Figure 6: Relation between amplitude averages $m_{A,ijk}$ and intensity averages $m_{I,ijk}$ of captured voltage AE signals

3.2 AE bursts after laser cutting

During laser cutting, continuous AE signals can be measured. They are characterized by changes in signal amplitude and frequency continuously in time. The AE signal will not end with the completion of laser cutting since wave amplitude exceeds the chosen amplitude measurement threshold (40 db). The analysis of laser cutting showed that for the process control the use of the continuous signals captured during laser cutting with a defined time interval of signal duration, i.e. 0.1 s, is appropriate. After the completion of laser cutting, the AE bursts in the plate can be captured. They usually have a lower amplitude value of the voltage signal than the continuous signals captured during laser cutting. Figure 7 shows characteristic captured acoustic emission after laser cutting. The number of the AE bursts sensed and the AE activity immediately after laser cutting will provide information on the events in the material after cutting.
The AE bursts captured after laser cutting show the initiation of cracking and peeling-off of the thin layer and the dross. Cracking of the oxide layer is caused by the differing expansion coefficients between the oxide layer and the substrate. The occurrence of the AE bursts can be attributed also to microstructural changes giving martensite [9, 10].

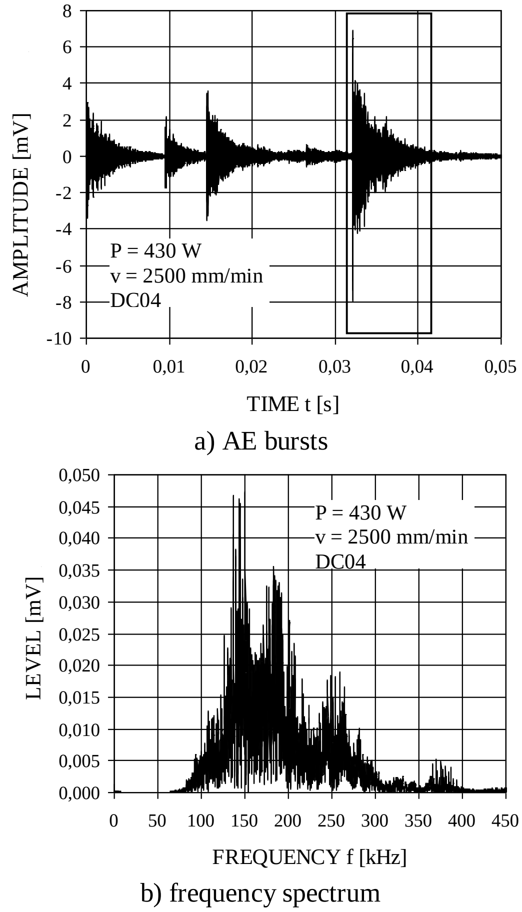
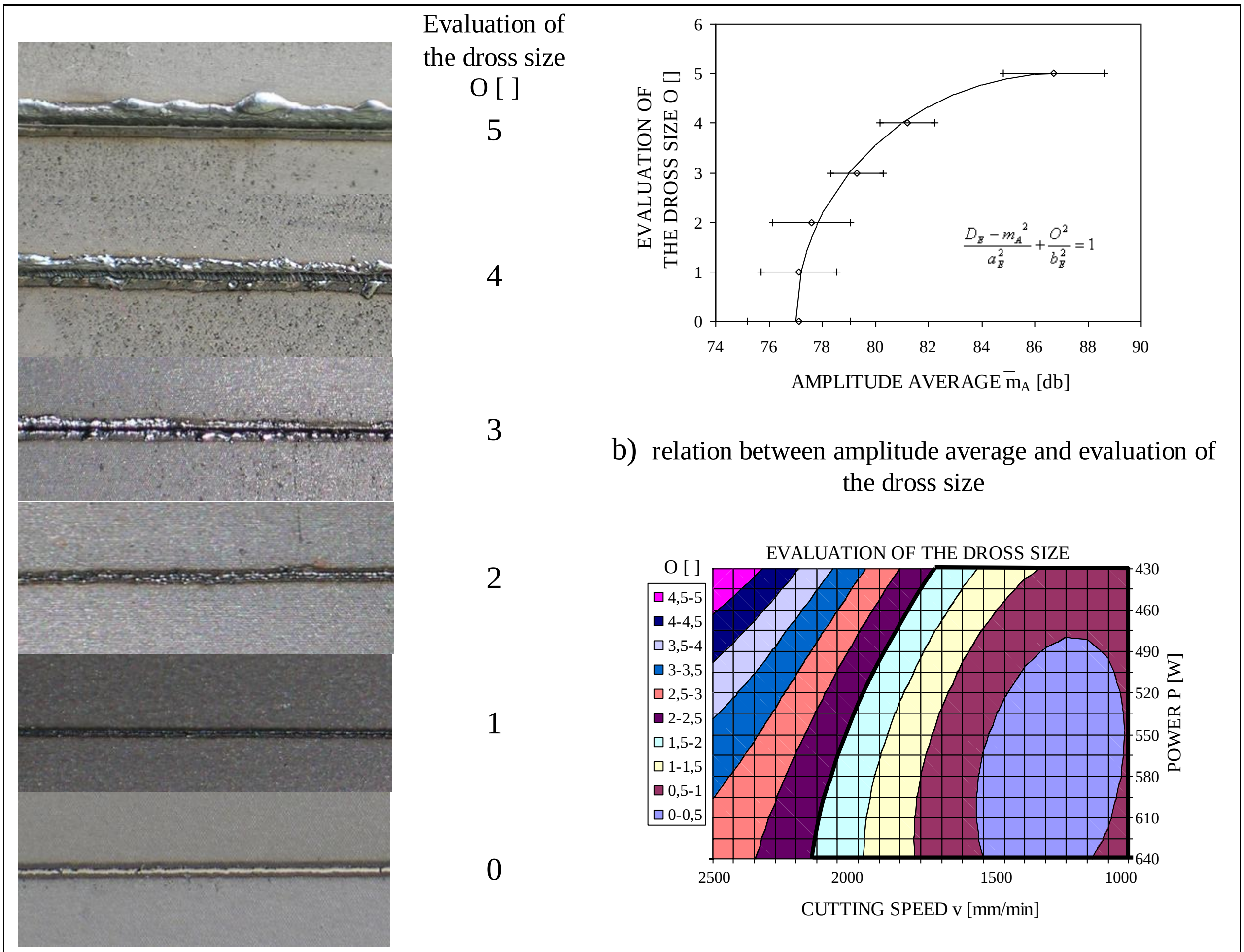


Figure 7: Captured AE burst after cutting and its frequency spectrum for given processing conditions

The phase transformations in the solid state produce internal stresses. The internal stresses are produced by the difference in density due to the changes of the crystal structure of the material during cooling-off of the cut surroundings and the difference in thermal expansion and shrinkage of individual microstructural phases in the material. The changes of internal stresses produce AE bursts because of the formation of microcracks or material microplastification. In case of diffusion transformation of austenite into ferrite and pearlite no AE bursts can be sensed although the formation of internal stresses due to the transformation concerned may be expected. The events consisting in a fast increase of the amplitude value of the AE signal and further signal attenuation in an exponential form indicate the initiation and propagation of microcracks. The location of microcrack initiation and propagation is usually related to the dross at the lower edge of a cut and the changes in the narrow heat-affected zone of the cut. A very limited plastification zone may produce the initiation and propagation of microcrack next to the cut. Stress concentration around pores and possible non-metal inclusions may also produce the initiation and propagation of microcracks.



a) reference images and evaluation of the dross size

b) relation between amplitude average and evaluation of the dross size

c) applicable range of the laser-cutting conditions

Figure 8: Assessment of cut quality by means of the dross size

3.3 Assessment of cut quality from an AE signal

The separation of a material in laser cutting consists in blowing-off of the molten material. Blowing-off of the melt from the cutting front forming is related to a pressure gradient and friction force exerted by the cutting gas. Poor flowing of the melt from the cutting zone will produce poor quality of a laser cut. The capability of flowing of the melt from the cutting zone is related also to a temperature dependence of the surface tension of the melt. The persisting and solidified melt at the lower edge of the cut has a form of a droplet. The solidified droplet formed remains attached to the lower edge of the cut and is called "dross".

A statistical analysis of a dross height and width measured at metallographic specimens shows strong dissipation of the dimensions. Consequently, it was decided to grade the dross size at the lower edge of the cut with grades between 0 (perfect – no dross) and 5 (poor – large dross). Figure 8a shows reference images of the lower edge of a laser cut and the way the cut quality was assessed by means of the dross size.

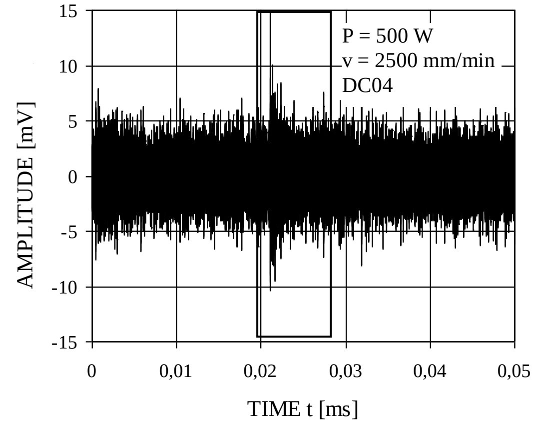
The relation between the amplitude average of the continuous AE signals m_A and evaluation of the dross size (O) was described with a canonical equation in the form

$$\frac{D_E - m_A{}^2}{a_E^2} + \frac{O^2}{b_E^2} = 1 \qquad (12),$$

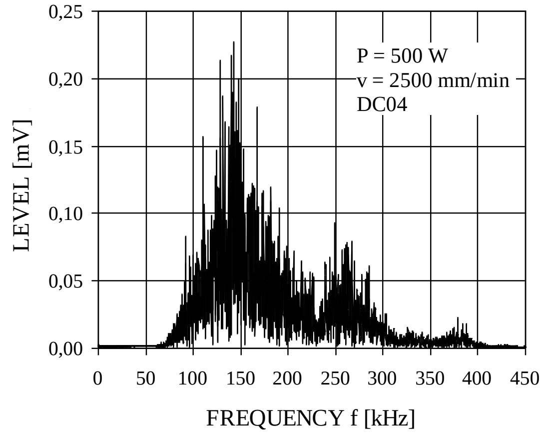
$$O = \sqrt{b_E\left(1 - \frac{D_E - m_A{}^2}{a_E^2}\right)} \qquad (13),$$

where D_E = 87 db is the deviation of ellipse from a coordinate centre, a_E = 10 db and b_E = 5 are semi-axis of the ellipse in the direction of the coordinate axes.

Figure 8b shows a relation between the amplitude average m_A and evaluation of the dross size. It confirms that with increasing dross size at the lower edge of the cut the amplitude value of the AE signals is increasing as well. Presuming that the grade of a still acceptable dross size is 2, we can define the applicable range of the laser-cutting conditions. This range is marked with a thicher curve in Figure 8c.



a) continuous AE signal



b) frequency spectrum

Figure 9: Continuous voltage signal of AE and frequency spectrum of marked portion of acoustic waves in the dross formation at lower edge of cut.

An analysis of the waveform and frequency spectrum of the AE signal captured indicates a relation between the increase of the amplitude value of the voltage signal in the dross formation at the lower edge of the cut. Figure 9a shows the continuous AE signal and a AE burst in the continuous signal, which increases the amplitude value of an individual continuous signal lasting 0,1 s. Figure 9b shows a frequency spectrum of the marked burst in the continuous signal. The waveform and frequency spectrum of these AE bursts in the continuous signal are very similar to the bursts captured in the solidification and material cooling phase after laser cutting. The AE bursts in the continuous signal are related to the occurrence of solidification and cooling of the molten substrate and oxides at the laser cut, which is related also to the formation of the dross.

4 Conclusions

The analysis made of the AE in laser cutting of plate DC04 confirms the following:

- The laser-beam power and cutting speed have a significant influence on the amplitude average and intensity average of the continuous voltage signals of AE in the material.
- The statistical analysis of both characteristics of the signals captured confirmed that the cutting conditions have a more distinctive influence on the amplitude average than on intensity average of the continuous AE signals, but for a more precise diagnostics of the process state simultaneous monitoring of both parameters of the AE sensed is suitable.
- A relation was established between the amplitude average of the continuous AE signals captured and the evaluation of the dross size at the lower edge of the cut. The increased dross size, characteristic of the poorer cut quality, can be efficiently confirmed by increasing the amplitude values of AE signals.
- The analysis of the waveform of the acoustic voltage signal indicates the presence of AE bursts in the continuous signal. The AE bursts can be related to the initiation and propagation of cracks, particularly in the oxide layer, partially in the heat-affected zone, and, to a certain degree, also to the martensite transformation during material cooling.

The relation established among the characteristics of the continuous AE signal captured during laser cutting and the cut quality accomplished permits efficient on-line monitoring and optimisation of the laser cutting process.

References

[1] P.O. Moore, R.K. Miller, R.K. Hill (eds), *Nondestructive Testing Handbook, 3th Edition, Volume 6, Acoustic Emission Testing*, American Society for Nondestructive Testing, INC., 227--270, 2005.
[2] W.W. Duley, *Laser Welding*, John Wiley and Sons, New York, 67--223, 1999.
[3] J.M. Slabe, T. Kek, J. Grum, *Measurement of acoustic emission and deformations in laser cutting of deep-drawn sheet parts*, 8th Int. Conf. of the Sovenian Society for NDT, Portorož, Slovenia, 2005. Conf. proc. Slovenian Society for NDT, 323--333, 2005.
[4] G. Chryssolouris, P. Sheng, F. von Alvensleben, *Process Control of Laser Grooving Using Acoustic Sensing*, Transactions of the ASME, Vol. 113, 268--275, 1991.
[5] T. Kurita, T. Ono, N. Morita, *Study on the Relationship Between Laser Processing Sound and Material Removal Characteristic*, Journal of Materials Processing Technology, Vol. 97, 168--173, 2000.
[6] D.C. Montgomery, *Design and Analysis of Experiments*, John Wiley and Sons, New York, 126--289, 2000.
[7] K. Chen, Y.L. Yao, *Striation Formation and Melt Removal in the Laser Cutting Process*, Journal of Manufacturing Processes, Vol. 1, No. 1, 43--53, 1999, str.
[8] E. Beyer (edt.), *Schneiden mit CO_2 Lasern*, VDI-Technologiezentrum Physikalische Technologien, VDI Verlag GmbH, Düsseldorf, 83--102, 1993.

[9] S.M.C. Bohemen, M.J.M. Hermans, G. Ouden, *Monitoring of Martensite Formation During Welding by Means of Acoustic Emission*, Journal of Physics D: Applied Physics, Vol. 34, 3312--3317, 2001.
[10] L. Grad, J. Grum, I. Polajnar, J.M. Slabe, *Feasibility study of acoustic signals for on-line monitoring in short circuit gas metal arc welding*, International journal of machine tools & manufacture, Vol. 44, No. 5, 555--561, 2004.